

Surface Support Systems for Co-Operative and Integrated Human/Robotic Lunar Exploration

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ABSTRACT

Human and robotic partnerships to realize space goals can enhance space missions and provide increases in human productivity while decreasing the hazards that the humans are exposed to. For lunar exploration, the harsh environment of the moon and the repetitive nature of the tasks involved with lunar outpost construction, maintenance and operation as well as production tasks associated with in-situ resource utilization, make it highly desirable to use robotic systems in co-operation with human activity.

A human lunar outpost is functionally examined and concepts for selected human/robotic tasks are discussed in the context of a lunar outpost which will enable the presence of humans on the moon for extended periods of time.

Introduction

Exploration of the solar system has been underway for many centuries. First with the aid of telescopes and mathematical deductions, and more recently in the twentieth century, with space flight by humans and robotic spacecraft sent to destinations that were simply beyond human reach. Meanwhile, activities in low earth orbit showed very promising results as humans collaborated with machines in a co-operative and integrated manner. Accomplishments such as the Hubble Space Telescope (HST) and the International Space Station (ISS) construction activities show that humans with appropriate support systems, proper planning and training can be highly productive and flexible while working in the space environment.

However, it is the hostile environment in space that precipitates the use of robotic devices and embedded control systems. Humans should not be endangered whenever possible and hazardous, routine, repetitive or mundane tasks can be handled by robotic assistants with appropriate systems design. This co-operative philosophy must be integrated into the design requirements of any space exploration system in order to maximize the usefulness of humans in space as well as to justify their presence. Humans working in

conjunction with robotic systems can be extremely effective since this increases productivity and frees the human to engage in an important aspect of exploration. This relies not only on rigorous scientific methods but also on flexibility, curiosity, serendipity, and intuition.

History of Lunar Exploration

On January 13, 1966, the Russian Luna 9 spacecraft made the first soft landing of a spacecraft on the moon [1]. This was followed by a series of attempted, and some successful, robotic Soviet Union and American lunar orbiters and landers. The cold war between these nations was the driving force of a competitive "space race" where successes in space were translated into political victories, even though significant scientific knowledge was gained about the moon. The first human landing was by Apollo 11 on July 20, 1969 and 5 subsequent human landings were achieved in the Apollo program [2]. The Apollo program consisted of 33 flights, 11 of which had a human crew. The 22 uncrewed space flights were conducted to qualify the launch vehicle and spacecraft for human flight [2]. Apollo 13 suffered an explosion of the number 2 oxygen tank in the Service Module (SM) but used the resourcefulness of its human crew and mission control support to safely return back to Earth. The final moon mission in the Apollo program was Apollo 17 on December 11, 1972 [2]. Subsequent Apollo missions such

as the Apollo-Soyuz Test Project rendezvous and docking with the Soviets in low earth orbit (July, 1975) focused more on collaboration in a political era of détente, and with the end of the space race, interest in the moon dwindled.

Recent NASA Lunar Studies

After the Apollo program had achieved its primary political goals, it became apparent that a long term space vision for the moon did not exist in the United States government. Budget realities and other national concerns caused a neglect of lunar exploration planning throughout the late 1970's and the early 1980's. In the late 1980's, NASA started to re-examine potential missions to the moon. Several case studies were performed in 1988 and 1989, dealing with human exploration of the moon and Mars [3]. In 1989, NASA conducted the "90 Day Study" which considered the moon as a test bed for Mars missions and also considered establishing a lunar outpost. This was followed by the "Synthesis Group" in 1991, which studied Mars exploration and science goals for the moon and Mars.

In the 1990's NASA was busy with the Shuttle and ISS programs which were the primary priorities, but a variety of human exploration studies were conducted for the moon such as "First Lunar Outpost (FLO) in 1993, Early Lunar Resource Utilization in 1993 and Human Lunar Return in 1996. Mars exploration also became a topic of much interest as the robotic science missions to Mars enjoyed spectacular success. In addition the Mars meteorite, ALH84001 (*Allen Hills, 1984 #001*) was found in Allen Hills, Antarctica in December 1984 by a team of US meteorite hunters, and Dr David McKay of NASA hypothesized in 1996 that it contained a fossil of possible bacterial life. This ignited new Mars exploration themes such as the "Search for Life" and "Follow the Water". Several Mars Exploration missions studies were performed between 1994 and 1999 which were designed to test the feasibility and technology readiness levels of doing a human Mars mission directly without going to the moon first. The early 2000's marked a shift away from Mars or moon studies as the "Earth's Neighbourhood" was considered. Asteroid missions and libration point telescopes were studied as human/robotic exploration destinations. On February 1st, 2003, the Columbia accident occurred, where

the Space Shuttle orbiter and its crew of 7 astronauts were lost on re-entry to Earth. This created a new reality at NASA, as the United States realized that a re-invigoration of the space program was necessary to remain as a pre-eminent space faring nation. Many studies and debates both inside NASA and outside NASA (in industry, academia and the public) were considered and a new era started at NASA on January 14, 2004 when President George W Bush announced a new space policy, the "NASA Vision for Space Exploration (VSE)". [4]

NASA Vision for Space Exploration

"The fundamental goal of this vision is to advance U.S. scientific, security, and economic interests through a robust space exploration program. In support of this goal, the United States will:

- Implement a sustained and affordable human and robotic program to explore the solar system and beyond;
- Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations;
- Develop the innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration; and
- Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests. "[4]

The new policy mandates that NASA should use the moon as a Testing Ground For Mars and Beyond and in a "renewed spirit of discovery" [4] the VSE called for the NASA space program to:

- Complete assembly of the International Space Station, including the U.S. components that support U.S. space exploration goals and those provided by foreign partners, planned for the end of this decade;
- Retire the Space Shuttle as soon as assembly of the International Space Station is completed, planned for the end of this decade;

- Develop a new crew exploration vehicle to provide crew transportation for missions beyond low Earth orbit
- Conduct the initial test flight before the end of this decade in order to provide an operational capability to support human exploration missions no later than 2014;
- Conduct the first extended human expedition to the lunar surface as early as 2015, but no later than the year 2020;
- Use lunar exploration activities to further science, and to develop and test new approaches, technologies, and systems, including use of lunar and other space resources, to support sustained human space exploration to Mars and other destinations.
- Conduct human expeditions to Mars after acquiring adequate knowledge about the planet using robotic missions and after successfully demonstrating sustained human exploration missions to the Moon." [4]

lunar base. For the purposes of this paper, a lunar outpost is defined as a human/robotic facility that can support rotating human crews for visits with durations of 6 months. The lunar outpost may be fixed at one location or may be mobile so that it can be moved to new locations with different points of interest. This outpost may then evolve into a permanent lunar base which is a settlement on the moon that has permanent infrastructure at a given location. Humans can inhabit the lunar base for periods of one year or longer and provide a continuous presence with a tangible outcome.

A good Earth analogue for such a lunar base is the Amundsen-Scott South Pole Station, an American research station at the South Pole, in Antarctica. The research station is remote, with a harsh climate and requires substantial logistics to maintain and operate it. A lunar base could be operated in a similar way allowing visiting guests, such as researchers, to conduct their work while a facility crew operates the base and oversees logistics.

In order to support the VSE, lunar exploration must be sustainable and must provide a lunar outpost if a permanent human presence is to be established leading to human settlement in a self sufficient lunar base.

The objectives of developing a lunar outpost (which will lead to a base) must be clear and justified in order to gain support from the public and capture the imagination of the next generation. The stakeholders who are users of the lunar outpost will also be a driving force behind the success of the outpost. The objectives of these stakeholders must be addressed in order to create a useful facility which produces tangible results. For the purposes of this paper, the following objectives are proposed.

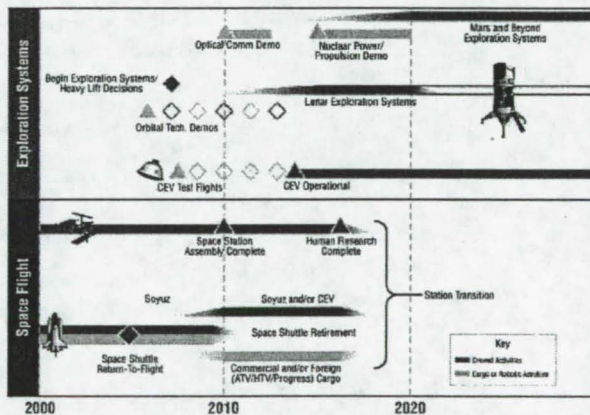


Figure 1: NASA Vision for Space Exploration

As of September 2006, the role of a lunar outpost remains unclear in the context of the VSE and NASA is performing surface objectives studies as well as lunar surface architecture studies, to lay out options for the lunar surface mission.

Lunar Outpost vs. Lunar Base

A lunar outpost is the first step in developing the surface assets and surface support systems that will eventually evolve into a

The primary objective of the lunar outpost is to:

Enable a permanent presence of human life on the surface of the moon with crew and cargo rotations every 6 months.

The secondary objectives of the lunar outpost are to:

- Support exploration of the lunar surface and sub-surface.
- Support science and research activities on the moon
- Demonstrate the feasibility of self sustenance using local resources

- (iv) Investigate commercial opportunities
- (v) Inspire the next generation of humans
- (vi) Take the first small steps towards extending a human presence across the solar system and the universe

Since the objectives must be coherent with the stakeholders needs, it is necessary to identify the stakeholders and their goals:

US Public – wishes to have their tax dollars spent in ways which will improve the nation and their quality of life on Earth.

Next Generation (Youth) – desires an ever improving world and inspiration for their future in it.

US Government Leadership – creates public policy that will enhance the nation's prosperity and well being.

NASA – responsible for implementing space policy successfully, in an economical way.

Scientists/Researchers – seek knowledge about the moon and related topics to further understanding in their respective fields.

Commercial Entities – seek a business opportunity that can yield a healthy return on investment.

International Partners – wish to engage in a bi-lateral venture to benefit both parties

Security - Verification and enforcement of international agreements such as the United Nations Moon treaty of 1979, Article 3 (not ratified by the USA, China or Russia)

Pioneer Settlers – wish to have a self sustaining settlement with a good quality of life.

The NASA goal is to move on to human exploration of Mars, so it is vital that the lunar outpost should not consume all of the NASA resources, therefore part of the lunar outpost objectives must include a NASA exit strategy. The lunar outpost must evolve to become the Lunar base in such a way that the stakeholders can meet their needs with a minimum of NASA government involvement.

The location of such a lunar base will be critical in determining whether the stakeholders objectives will be met and is therefore a large factor in the eventual success of a self sustaining lunar base. A lunar outpost may be mobile in order to facilitate exploration of the moon and its resources, but a lunar base should be fixed to allow for an infrastructure build-up. Past history on Earth has taught us that a settlement can be more

successful when it is associated with useful resources. This means that the outpost should be used for scientific research and as a prospecting system. The lunar base can then be established at the site with the best mixture of resources and points of interest.

Sustainability & In-Situ Resource Utilization

There are two primary challenges that make it difficult to achieve a settlement on the moon; the cost of the venture and the technological "know-how".

The cost of transportation is very high, exceeding US\$10,000 per pound (\$22,046 per kilogram),[1] in the United States in 1998. Commercial entities in other nations such as Russia, India or China may be able to provide lower launch costs but the cost is still prohibitive.

In addition, the trans-lunar injection stages, spacecraft and support systems for transportation from low earth orbit must be developed, manufactured, tested, flown and operated, which requires more investments. A significant technological base and an established spaceflight capability must exist in order to provide a successful and safe lunar outpost solution.

These factors imply that new approaches must be used in space flight and surface operations in order to reduce the cost and increase the reliability and maintainability of the surface systems that will form the lunar outpost.

The moon has many local resources that can be used to help sustain life on the moon. If these resources can be exploited at a life-cycle cost that is lower than simply transporting equivalent materiel from the Earth, then it will be economical to produce the materiel locally on the moon. In addition, a production surplus at the lunar outpost can be the genesis of a commercial trade, as commodities such as energy and oxygen can be exported to help sustain the lunar economy.

Since such a lunar economy has a high barrier to entry due to start up costs associated with establishing a lunar outpost, it is reasonable to propose that the US government should invest in the establishment of a lunar outpost in order to help nurture the fledgling lunar economy. Eventual commercial and scientific activity can then be used to benefit the United States budget through technology spin-offs,

intellectual capital, an increased knowledge base and normal business revenue taxation. The case has yet to be made that such an economy is feasible and it will depend on the availability of resources, user needs, details of implementation and technology maturation.

The resources that are available on the moon are listed below [1]:

- a.) Major elements in the regolith
- b.) Trace elements in the regolith
- c.) Physical characteristics of the regolith as a building material
- d.) Potential water in the polar regions
- e.) Sunlight
- f.) Vacuum
- g.) Temperature profile
- h.) Physical mass of the moon: gravity
- i.) Topography
- j.) Sterile environment
- k.) Low Gravity (1/6th Earth Gravity)
- l.) Near/Far Side of Moon: Tidal Locking

The following tables 1 and 2 show the proportions of elements that are available in the lunar regolith. The availability of these elements shows that if they can be mined, beneficiated, processed and distributed, then substantial elemental resources exist on the moon which can contribute towards the goal of self sufficiency in order to make a lunar settlement economically feasible.

Element	Average of Surface Percent of Atoms (%)
Oxygen (O)	60.9
Silicon (Si)	16.4
Aluminium (Al)	9.4
Calcium (Ca)	5.8
Magnesium (Mg)	4.2
Iron (Fe)	2.3
Sodium (Na)	0.4
Titanium (Ti)	0.3

Table 1: Major Elements in the Lunar Regolith [1]

Trace Elements	Gr/m ³ of Lunar Regolith (approx.)
Sulphur (S)	1,800
Phosphorous (P)	1000
Carbon (C)	200
Hydrogen (H)	100
Nitrogen (N)	100
Helium (He)	20
Neon (Ne)	20
Argon (Ar)	1
Krypton (Kr)	1
Xenon (Xe)	1

Table 2: Trace Elements in the Lunar Regolith [1].

The most obvious use of the major elements is the extraction of oxygen for use as a propellant oxidizer, breathing air consumables and power fuel cell consumables. Hydrogen may be available in the form of water ice at the polar regions. This has been heavily debated since the Clementine and Lunar Prospector missions found evidence of a significant amount of hydrogen atoms, and it is not known yet whether the ice actually exists and if it can be mined and exploited.

The resources that are available on the moon can all contribute to In-Situ Resource Utilization (ISRU) in a variety of ways such as; construction and manufacturing materials, energy from the sunlight, energy and thermal management through temperature gradients between sunlit and shadowed areas, Earth Observation from the near side and radio interference free space observation on the far side. In addition, agricultural food and fiber resources can be grown on the moon if water is available. Other ISRU applications will be developed over time as the lunar economy grows.

Lunar Outpost Functional Concept

A concept for a human lunar outpost is one that consists of 6 major functional areas:

- 1) Landing/Launch Pad
- 2) Habitation and Laboratory Area
- 3) Power Production Area
- 4) Propellant/Water Production & Storage
- 5) Surface Equipment Storage Area
- 6) Exploration & Mining Area

These areas are summarized in the functional block diagram below:

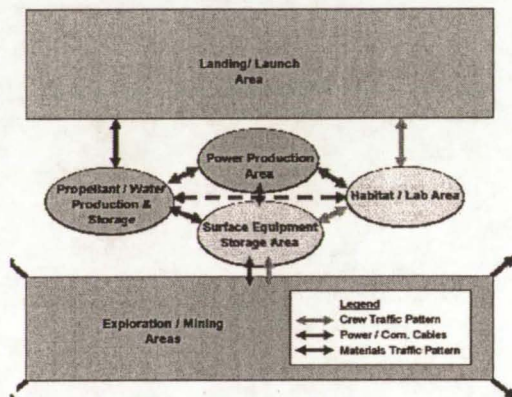


Figure 2: Lunar Outpost Functional Block Diagram [5]

The primary work areas for the humans are the Habitat (Hab) and Laboratory (Lab) areas; they interact with equipment for maintenance and checkout at the Surface Support Storage Area. The other areas are primarily dedicated to robotic or self-controlled systems.

Sorties from the lunar outpost in various forms of surface mobility such as rovers or hopper platforms, can enable global lunar access for science and exploration activities, but the crew always returns to the outpost for replenishment and a safe haven. All human traffic to and from the moon is via the outpost landing and launch pad area, which has mitigation devices such as surface stabilization or regolith berms to avoid damaging other surface assets with blast ejecta. Separation distances are dependent on specific design solutions, but notional dimensions could be a 400 meter diameter circle for the outpost area, with a 500 m. separation distance from the landing/launch pad of 100 m. diameter (for pinpoint landing). A solar power production plant could be adjacent to the outpost living area, while a nuclear power plant could require a separation distance of as much as 1000 m. If the nuclear power plant was buried to a depth

of 6 m, then the separation distances could be drastically reduced to 100 m. or less.

The crew traffic, power, communications (comm.) flow and the materials traffic pattern are indicated by arrows in figure 2. This implies that pathways and cables must be deployed to establish these interfaces.

Human Robotic Cooperation: Concepts for Selected Tasks

Surface Preparation and Construction of a Landing and Launch Area

The first human lunar lander that arrives at the outpost landing site will land on natural terrain. Subsequent landers that will add to the outpost deployment must land close to the previously deployed assets so that they can be assembled or used in close proximity. During landing on an unprepared surface, the rocket engine plume of the lander will cause regolith blast ejecta and dust entrainment. This could jeopardize the landing due to poor visibility, foreign object debris (FOD) impact, or cause damage to the previously deployed assets of the outpost. To avoid this potentially catastrophic scenario, an area of the surface can be prepared to remove the top 15-20 cm of the regolith below which the regolith is substantially more compacted and less likely to be ejected. For a pinpoint landing using navigational aids or an onboard visual navigation system, this landing and launch pad area is estimated to be a circle with a diameter of 100 m. In addition, regolith berms can be constructed around the side of the perimeter that faces the outpost location in order to guarantee that no ejecta can damage the outpost, although this concept requires further study regarding the likely debris ejecta angles. Such a landing/launch pad allows for multiple landings of human and robotic landers in a safe and efficient manner.

Deployment of a Power Plant

The history of exploration and settlement have shown that it is far more likely to be successful if the outpost is in a power rich condition. This means that there is more than sufficient power available for routine operation as well as contingency peaks of higher power consumption. The highest priority in the early outpost development stage will be to establish a secure and reliable power plant which is estimated to have a

capacity of 50 KWe or higher. If such a power plant could be robotically landed, deployed, and checked out, then the crew would be assured of a power rich scenario on the first mission in the outpost campaign.

Various power plant and power storage options have been proposed, and the two most likely options are solar power and nuclear power. Solar power could be landed with each lander in the form of modular deployable solar panels which would incrementally build up with each mission to the final area required. Alternatively a dedicated large solar power plant could be deployed as a single unit with gimbaling arrays.

Nuclear power plants face similar packaging and deployment issues, but they also require large radiators to dump excess heat and a form of radiation mitigation or protection. The nuclear power plant can be placed at a distance of 1-2 km from the outpost, or it can be shielded to reduce the level of radiation exposure to an acceptable level of 5 rems/year or less [1]. An attractive solution is to bury the nuclear reactor in a hole in the regolith which is estimated to be 6m deep and 1 m diameter. If the nuclear power plant is buried, then humans can approach the plant surface components and radiators for maintenance and it can be co-located with the outpost. Such a hole digging, placement and burying task can be achieved either totally robotically or by humans with the aid of robotic assistants for digging and placement of the power plant reactor.

Shielding of Human Living and Working Spaces

Radiation occurs naturally in the lunar environment as a result of solar particle events (SPE) from the sun and galactic cosmic radiation (GCR). Since there is no magnetosphere to protect the humans on the surface from this radiation, it can be extremely dangerous to human health if these levels get too high (>5 rems/year) [1] or if a cumulative long term exposure limit is surpassed.

Shielding and shelters are recommended to ensure the safety of the crew, but this implies a large mass penalty if it is brought from Earth. Fortunately, the lunar regolith can be used as radiation shielding, but requires a minimum thickness of 2-3 m (400 gm/cm³) to avoid secondary radiation effects from incoming particles. [1]

In addition, the large thermal swings and gradients on the moon (127 C to -173 C) [1] require thermal management of the living spaces. Regolith is a good insulator material and the same shielding used for radiation can be used to mitigate the thermal swings to provide an average constant temperature of -20 C [1].

Micrometeorites are an ever present phenomenon on the moon. A third use for the regolith shielding is to prevent the micrometeorites from damaging the human living areas.

Since relatively large quantities of regolith must be excavated and placed on the surface assets to shield them, this task is well suited to a robotic excavator device which would also place the regolith on the surface asset.

The Search for Water

The presence of water at an outpost has major implications since hydrogen and oxygen elements can be extracted from water quite simply by the use of electrolysis. While it is still debatable whether the water actually exists or if it is in a form that can be accessed in the regolith or extracted, if it does then it would be highly desirable to mine it and use it. The hydrogen and oxygen can be used as fuel and oxidizer for propulsion systems which range from ascent vehicles to hopper vehicles to fuel cell driven surface mobility. In addition, there are hydrogen reduction methods for extracting oxygen from the regolith and in this case the hydrogen would not have to be brought from earth. Water for human consumption and water for plant growth are also highly desirable. The presence of water would have a large effect on the mission mass, especially if it could be used for ascent stage propulsion systems.

The topography of the craters that may contain water is rather steep and hazardous. The slopes range from 15 degrees to vertical and access is challenging. In addition, if the water does exist then it is likely that it will be in the cold traps of the crater or the permanently shadowed regions, which never warm up. The water is likely to be mixed with the regolith which must be excavated and the separated in situ or transported to the production area for water extraction and distribution. These aspects of the search for water on the moon make it well suited for a mobile robotic walker or other robotic mobility system. The robotic prospector and miner

robot can operate in a hazardous environment over extended periods of time to produce water for human use in an outpost.

Regolith Excavation for ISRU O₂ Production

Oxygen exists in abundance on the moon as one of the major elements on the regolith. There are various ways of extracting the oxygen from the regolith that have been demonstrated in laboratories on Earth. Some examples are hydrogen reduction, carbo-thermal and molten salt processes. Both the mare and the highlands have regolith which contains oxygen. Therefore the production of oxygen from regolith is suitable at almost any location on the moon.

Regolith must be excavated and delivered almost continuously while the ISRU production plant is operating. The regolith excavation rates are estimated to be in the range of 50 kg/hour to 100 kg/hour. It is likely that the regolith will be obtained from the top surface layer of the surface which is loosely bound and deep digging will be avoided, in this case, in order to simplify the task. A robotic excavator hauler device can excavate the top 15 cm of regolith over an area to support oxygen production of approximately 10 metric tonnes per year for the outpost. This oxygen can be used for ascent stages and consumables. Since the previously mentioned task of preparing a launch pad requires the excavation of similar amounts of regolith, then there is a possible dual use application of the regolith excavated on the landing/launch pad for the ISRU plant feedstock.

Surface Mobility for Exploration and Science

Science and exploration of the moon dictates that the crew should leave the outpost and make discoveries at diverse locations. Extra Vehicular Activity (EVA) in un-pressurized rovers and Intra-Vehicular Activity (IVA) in pressurized rovers will give the astronaut crew mobility. While on EVA, the humans can use robotic assistants which may be part of the un-pressurized rover or may be towed or self propelled as a separate unit. "Mule robots and other robotic assistants can support the humans and increase their productivity. While operating from a pressurized rover, the humans can use robotic manipulator devices and a built in "glove box" to access the lunar

surface and then perform an EVA only when interesting situations or targets arise.

Outpost Surface Support Equipment Concepts

In order to perform the tasks required to operate an outpost and live in it, a variety of surface support equipment (SSE) is required to operate it. The nature of the equipment is human operated and robotic. The robotic equipment is controlled with tele-operation from Earth and semi-autonomous embedded control systems for selected sub-tasks.

Examples of such SSE are described below. There is a substantial amount of equipment that must be operated and ways must be found to do so without overwhelming the astronauts. In many cases there are robotic solutions which will alleviate the astronaut crew from time consuming EVA tasks and potentially hazardous situations.

The mass, power and volume consumed by these systems must be reasonably transported by lunar transportation systems such as a human lunar lander and a cargo lunar lander. The cargo capacity provided by the human lunar lander is 1000 to 2000 kg while the cargo lander can deliver from 17,000 to 20,000 kg of equipment in an 8 m. diameter by 10 m long volume.

During outpost operations, a variety of equipment is necessary in the following categories:

Launch & Landing Support

- (i) Launch Support
- (ii) Landing Support
- (iii) Propellant Handling & Consumables Support
- (iv) Utility Connections & Interfaces
- (v) Hazard Detection & Suppression

ISRU O₂ Consumables & Power Related

- (i) Mining & Resource Acquisition Support
- (ii) Resource Transfer Support

- (iii) Resource Beneficiation Support
- (iv) O₂ Production Support
- (v) Water Storage & Distribution
- (vi) Power System Support

Access & Handling

- (i) Personnel Lift & Access Devices
- (ii) Mobile Cranes & Heavy Lifting
- (iii) Medium & Small Cargo Handling
- (iv) Inspection & Maintenance Access
- (v) Crew Extra Vehicular Activity (EVA)
Steep Terrain Access

Surface Transportation Accessories

- (i) Rover Attachments
- (ii) Traction Devices and Surface Anchors
- (iii) Maintenance Equipment
- (iv) Navigation Accessories
- (v) In-Situ integrated Systems and Components

Surface Preparation and Surface Construction

- (i) Surface Preparation and Pathways
- (ii) Excavation, Trenching & Tunneling
- (iii) Structure Foundation & Fabrication
- (iv) Radiation, Thermal, Micro-Meteorite and Rocket Plume Debris Shielding

Hazardous Materials & Waste

- (i) ISRU Waste Stream Management
- (ii) Human Waste Stream Management
- (iii) Radioactive Waste Management

Conclusions

NASA has embarked on a new journey that will be the first steps towards extending a human presence across the solar system and eventually the universe. This policy was announced in the US Vision for Space

Exploration in 2004, and is currently being implemented.

Although NASA has not announced any plans for a lunar surface architecture yet, this paper has examined areas in which human and robotic systems could interact to enable the development of a lunar outpost. A major component of having a human presence on the moon is the development of a lunar outpost where humans can live for periods of up to 6 months before requiring a crew rotation and re-supply logistics.

A lunar outpost functional concept was presented and various selected human robotic cooperation task concepts were presented. A classification of surface support equipment that could be required for a lunar outpost was also presented.

It is the intention of the author that these concepts and equipment categories can stimulate thinking and new ideas on how humans and robots can interact in the development of a lunar outpost. This will eventually lead to the generation of requirements in the systems engineering process for building actual systems that will go to the moon to support the NASA vision.

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